Pristine chondritic meteorites: the rewards and challenges of unravelling the complex solar system record of these rare cosmic jewels

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Chondritic meteorites provide remarkable insights into the earliest stages of Solar System history, as well as a window into the characteristics of the molecular cloud material that was the precursor material of our Solar System. Chondrites contain a record of processes that occurred within the protoplanetary disk, providing an essential link between astrophysical observations of accretionary disks around young stellar objects. Although we have an abundance of chondritic meteorites, both falls and finds, in the world's meteorite collections, chondrites are rocks that have undergone a variety of processes, including aqueous alteration, metasomatism and thermal and shock metamorphism that have resulted in them being lithified and modified, typically within asteroidal environments. These processes have changed, to different degrees, the primary characteristics of materials that formed in the protoplanetary disk. Therefore, a primary challenge of cosmochemistry is to recognize and understand secondary processes that may have modified the primary signatures of protoplanetary disk processes. In this regard, identifying meteorites that have escaped, to a large degree, the effects of these secondary processes is of paramount importance, because they preserve this early primary record of solar system history with the highest fidelity.

Studies over the past 25 years have resulted in the identification of a small number of meteorites from different chondrite groups, which demonstrate that they are among the most pristine asteroidal samples available for study and, hence, are of major scientific significance. This group of select meteorites is growing at a slow, but nevertheless discernible rate, and now includes several meteorites, such as ALH A77307 (CO3), DOM 08006 (CO3), Acfer 094 (unique carbonaceous), QUE 99177 (CR), MET 00426 (CR), QUE 97990 (CM), and Paris (CM) [1-6]. Notable among this group of meteorites is the fact that almost all of them, except Paris, are either cold dry desert or hot dry desert finds, underscoring the major importance of collection activities in these different environments. However, this fact also requires that considerable care must be taken in identifying possible effects of terrestrial weathering that may be, in some cases, extremely subtle.

Standard petrographic methods for the classification of chondritic meteorites into the different petrologic types from 3 to type 6 observed in chondritic meteorites has relied to a significant degree on textural criteria, but also most importantly on the compositional characteristics of coarse-grained silicate phases, such as olivine and pyroxene in chondrules. The classification procedure of [7] has been a very useful tool in this regard. The breakdown of the type 3 chondrites into subtypes from petrologic 3.0 to 3.9 further enhanced the utility of this classification scheme. However, it has only been recognized recently that even type 3.0 chondrites exhibit subtle modifications to the chemistry of chondrule silicates that are the result of metamorphic processes. [8] demonstrated for type 3.0 unequilibrated ordinary and CO chondrites that the Cr content of type IIA chondrule olivines shows measureable changes and proposed a further subdivision of type 3.0 chondrites into petrologic types 3.00 to 3.09. This approach is now widely employed as a standard method for the classification of both ordinary and carbonaceous chondrites (CCs), coupled with the studies of metals [9] that are also highly sensitive to thermal metamorphism. The recognition that even chondrule silicates are affected by very low degrees of thermal metamorphism has profound implications for the study of the fine-grained matrices of chondrites, which are the host of both presolar grains and organic materials. The very fine-grained nature of matrix components makes them highly susceptible to both thermal and aqueous processing. Many early studies of chondrite matrices assumed that even petrologic type 3.2 or 3.3 chondrites contained pristine matrix materials, leading to a number of misconceptions about the nature of the primary nebular dust components of matrix, most notably the occurrence of very fine-grained FeO-rich olivine, commonly argued to be a nebular condensate [10].

Studies of the matrices of the most pristine type 3 chondrites – types 3.00-3.03, have revealed the primary mineralogical and textural characteristics of these materials and are beginning to dispel some of these early misconceptions. [1] showed that the matrix of ALH A77307 (CO) consists of a highly unequilibrated, complex and diverse assemblage of amorphous Fe-bearing silicate, crystalline silicates, sulfides, oxides and metals, ranging from the micron to nanometer scale. Most significantly, the most abundant component present in the matrix is amorphous silicate, which had not been recognized previously in CCs. In ALH A77307, this amorphous phase acts as a groundmass for the other phases and is distributed widely throughout the matrix and fine-grained rims. Further support that amorphous silicates are a significant component of pristine chondrites came with the discovery of the unique CC, Acfer 094 [3]. The discovery of CR chondrites, such as QUE 99177 and MET 00426 that are also very pristine [4], as well as the CO chondrite DOM 08006 [2] has confirmed the importance of amorphous silicates in very low type 3 and high type 2 chondrites and demonstrated they are an essential, diagnostic characteristic of the most pristine, unequilibrated chondrites.

Collectively, these pristine meteorites have provided a wealth of new scientific opportunities and revelations. Most notably, the first discovery of oxygen anomalous presolar silicate grains in CCs was made in Acfer 094 [11] and was followed by the confirmation of their presence in ALH A77307 [12]. Further, these meteorites have the highest abundances of oxygen-anomalous presolar silicate grains of any chondrites [13] and hence have contributed significantly to understanding the astrophysical origins and diversity of these grains. In particular, unlike other types of presolar grains, such as SiC, graphite, and diamond that can survive moderate degrees of metamorphism and aqueous alteration, presolar silicate grains, are highly sensitive to parent body processing and only occur in significant abundances in the most pristine chondrites [13].

One of the major discoveries of work on pristine chondrites is that they have all experienced some kind of secondary alteration. However, as is now very apparent for the CR chondrites, the matrix can have been affected by aqueous alteration, but still preserves extremely fine-grained amorphous presolar silicates [14]. QUE 99177, for example, contains among the highest presolar silicate grain abundances of any known chondrite, but has been classified as a petrologic type 2.8 chondrite [15]. A major conclusion of these studies is that even type 2 chondrites can be important sources of surviving fine-grained nebular and presolar grains, a notion that was not even considered prior to the discovery of QUE 99177 and MET 00426. Such observations show that type 2 chondrites should not be automatically ruled out as potential resources for studying the primary characteristics of nebular and presolar materials.

A further discovery of major significance is the recognition that some CM2 chondrites also contain significant abundances of amorphous silicates, rather than phyllosilicates. The discovery of amorphous silicates with possible links to GEMS in the weakly-altered Paris CM2 fall [6] is especially important in this regard. It is now apparent that other CM2 chondrites such as QUE 97990 [5] and Y-791198 [16] also contain significant abundances of amorphous silicates. Although these amorphous silicates are almost certainly hydrated [6,16], the fact that they have not recrystallized to form phyllosilicates suggests that they were altered at very low temperatures and hence may preserve presolar and nebular materials.

Conclusions and outlook: Based on our current knowledge, true petrologic type 3.00 chondrites that have had no interaction with aqueous fluids do not exist. All very low petrologic type chondrites appear to have experienced some form of aqueous alteration that has affected their matrices. However, despite these fluid-rock interactions, there is an increasing body of evidence that very fine-grained presolar and nebular grains are still preserved in the matrices of weakly-altered type 2 and 3 chondrites and have the potential to provide significant new insights into early solar nebular processes. Indeed, such meteorites may be more common in our collection than has previously been recognized, but require careful and detail studies to uncover.

References

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